Chapter 7
Soil-Structure Interaction Analysis

7-1. Introduction

The classical design procedures discussed in Chapters 5 and 6 rely on several simplifying and often contradictory assumptions regarding the behavior of the wall/soil system. Some of the anomalies contained in the classical procedures are:

a. Incompatible pressures and displacements. In both cantilever and anchored wall design, the soil pressures are assumed to be either the limiting active or passive pressure at every point without regard to the magnitude or direction of wall/soil displacements. In the case of an anchored wall, the tendency of wall motion to produce a passive condition above the anchor is ignored. The effects of wall and anchor flexibilities on soil pressures are ignored, and the displacements are calculated based on hypothetical, and perhaps, unrealistic supports.

b. Effect of pile penetration. Analysis by the classical methods of a wall with a penetration greater than that required for stability indicates not only an increase in the factor of safety but attendant increases in soil pressures, bending moments, anchor forces, and deflections as well. While the increased deflections are consistent with the assumptions in the classical procedures, an increase in penetration should be expected to result in reduced deflections.

c. Multiple anchors. Approximate methods of design have been proposed for walls with multiple anchors, however these methods introduce further simplifying assumptions regarding system behavior and suffer from the same limitations as those for single anchored walls.

7-2. Soil-Structure Interaction Method

The soil-structure interaction (SSI) method of analysis described in this chapter enforces compatibility of deflections, soil pressures, and anchor forces while accounting for wall and anchor flexibilities. The SSI method is based on a one-dimensional (1-D) finite element model of the wall/soil system consisting of linearly elastic beam-column elements for the wall, distributed nonlinear Winkler springs to represent the soil and nonlinear concentrated springs to represent any anchors.

7-3. Preliminary Information

Required preliminary information for application of the SSI method includes the system characteristics described in paragraph 5-2*b* as well as the penetration of the sheet piling, sheet piling material and cross-sectional properties (area, moment of inertia, and modulus of elasticity), and anchor properties (tie rod area, modulus of elasticity, and flexible length). These data will be available for analysis of an existing wall/soil system. For use of the SSI method as a supplemental tool in design of a new system, an initial design using one of the classical methods may be performed and the SSI analysis used to refine the design.

7-4. SSI Model

The one-dimensional model of a typical 1-foot slice of the wall/soil system is shown in Figure 7-1. Nodes in the model are defined at the top and bottom of the wall, at soil layer boundaries on each side, at the groundwater elevation on each side, at the anchor elevations and at other intermediate locations to assure that the length of each beam element is no more than 6 inches. Lateral support is provided by the distributed soil springs and concentrated anchor springs. At present, there is no acceptable procedure to account for the effects of wall friction or adhesion in resisting vertical motions of the wall. The effects of these factors are included in the assessment of the lateral resistance of the soil. When an inclined anchor produces axial force in the piling, the bottom of the wall is assumed to be fixed against vertical translation. Conventional matrix structural analysis is used to relate the deformations of the system (defined by the horizontal and vertical translations and the rotations of the nodes) to the applied external forces. This results in a system of 3N (for a model with N nodes) nonlinear simultaneous equations which must be solved by iteration. The details of the analytical procedure are presented in the CWALSSI User's Guide (Dawkins 1992).

7-5. Nonlinear Soil Springs

The forces exerted by the distributed soil springs vary with lateral wall displacement between the active and passive limits as shown in Figure 7-2. Active and passive soil pressures are calculated for a factor of safety of 1 by the procedures described in Chapter 4 including wall/soil friction and adhesion. The at-rest pressure p_o, corresponding to zero wall displacement, is obtained from

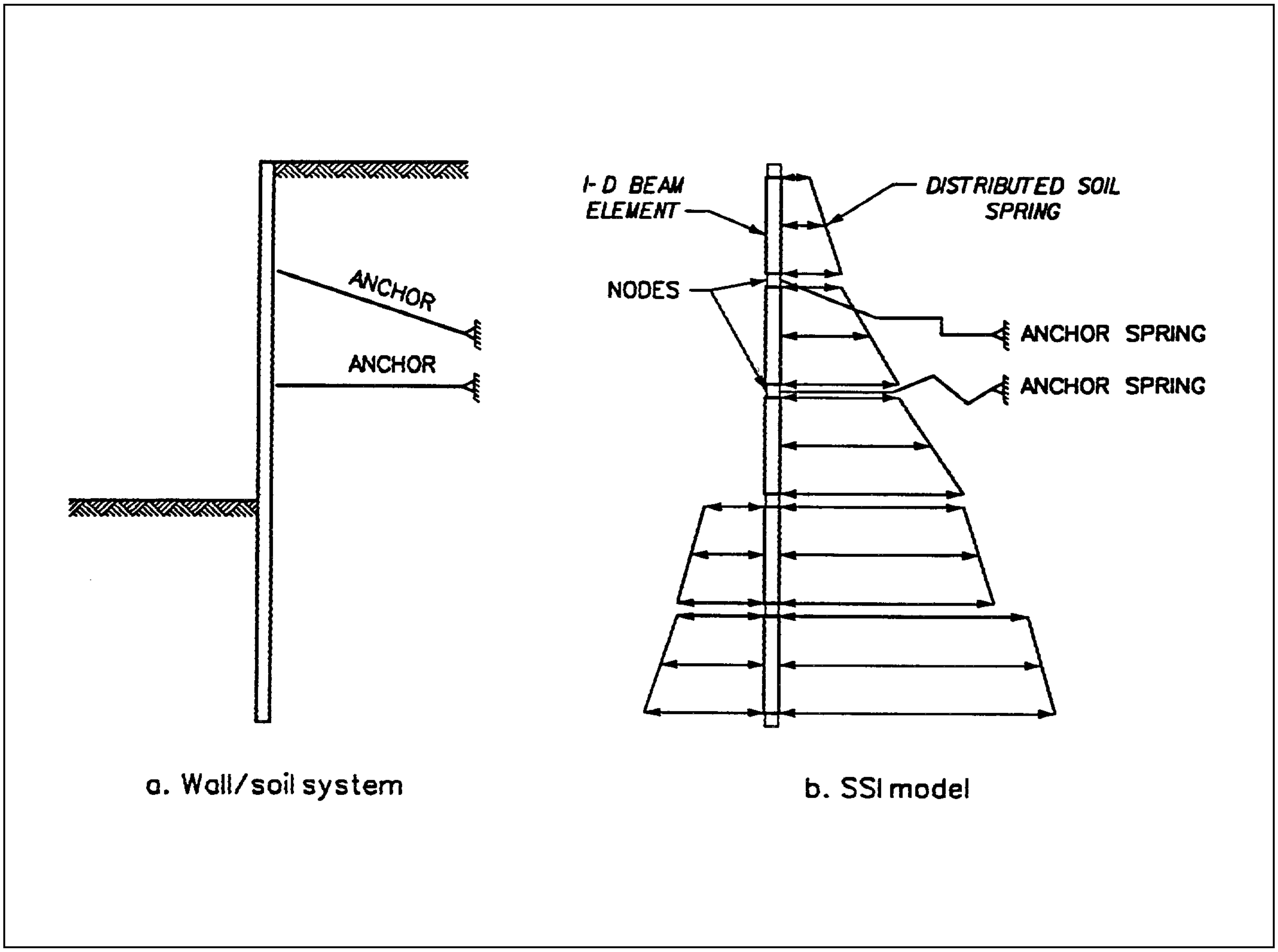

Figure 7-1. System for SSI analysis

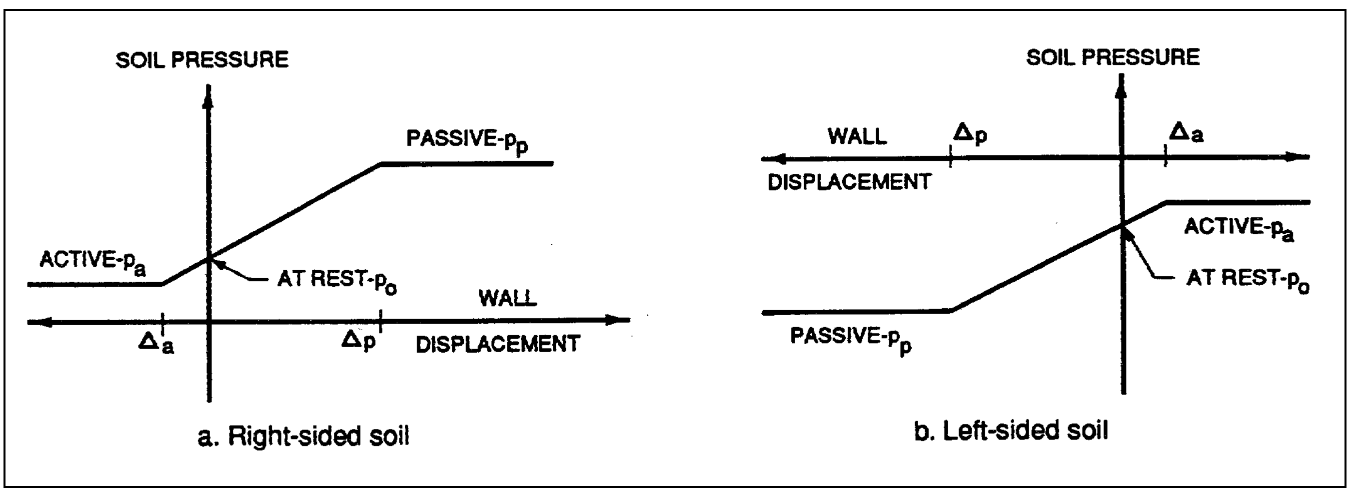

Figure 7-2. Distributed soil springs

$$p_o = p_v \ K_o \tag{7-1}$$

where

p_v = effective vertical soil pressure at the point of interest

K_o = at-rest soil coefficient

The at-rest coefficient should be ascertained by the geotechnical engineer during soil exploration. In the absence of test data, K_o may be estimated by

$$K_o = 1 - \sin(\phi) \tag{7-2}$$

Although the variation of soil pressure between limits follows a curved path, the simplified bilinear representation shown in Figure 7-2 is used. The displacements at which limiting active or passive pressure are reached depend on the type of soil and the flexibility of the wall. These influences are characterized by soil stiffness values and an estimate of the distance from the wall to which the soil is significantly stressed (the interaction distance). Rules-of-thumb for estimating the interaction distance are provided in the CWALSSI User's Guide (Dawkins 1992). Representative soil stiffnesses are given by Terzaghi (1955). With known values of soil stiffness, the transition displacements, p_a and p_p in Figure 7-2, for any node in the model are obtained for sand as

$$\Delta_a = \frac{p_o - p_a}{(s_a \cdot p_v)/(\gamma \cdot d)} \tag{7-3}$$

$$\Delta_p = \frac{p_p - p_o}{(s_p \cdot p_v)/(\gamma \cdot d)} \tag{7-4}$$

and for clay as

$$\Delta_a = \frac{p_o - p_a}{(s_a)/(d)} \tag{7-5}$$

$$\Delta_p = \frac{p_p - p_o}{(s_p)/(d)} \tag{7-6}$$

where

p_a, p_o, and p_p = active, at-rest, and passive pressures

s_a and s_p = active and passive soil stiffnesses, respectively

p_v = effective vertical soil pressure

γ = effective soil unit weight

d = interaction distance, all at the node of interest

7-6. Nonlinear Anchor Springs

Anchors are represented as concentrated nonlinear springs in which the force varies with wall displacement as shown in Figure 7-3. The limiting tension force is given by

$$F_t = A_r \ f_y \tag{7-7}$$

where

A_r = the effective area of the tie rod

f_y = yield stress of the material

The limiting force in compression F_c depends on the manner in which the tie rod is connected to the wales and the compressive axial load capacity of the tie rod (rod buckling) and may vary from zero to the yield value given in Equation 7-7. The displacements at which the linear variation of force ceases are given by

$$\Delta t = \frac{F_t \ L}{E \ A_a} \tag{7-8}$$

$$\Delta c = \frac{F_c L}{E \ A_a} \tag{7-9}$$

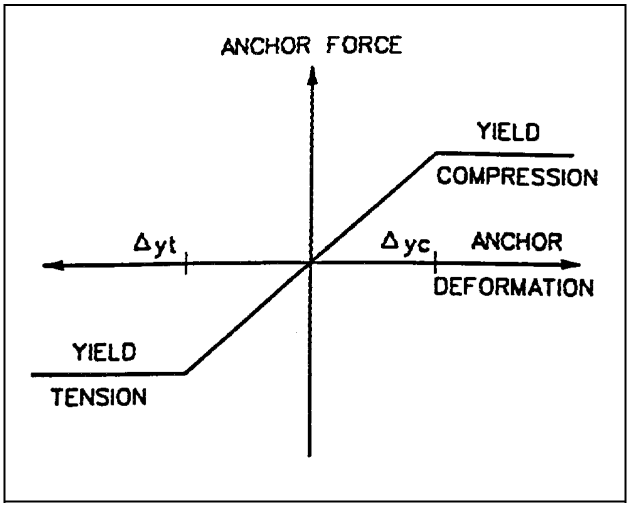

Figure 7-3. Anchor spring

where

L = length of tie rods attached to discrete anchors or the unbonded length of grouted anchors

E = modulus of elasticity of the rod

A_a = cross-sectional area of the rod

The force-deformation characteristic for cable tendons should be obtained from manufacturer's specifications.

7-7. Application of SSI Analysis

The SSI procedure provides solutions in which forces (bending moments, shears, anchor force, and soil pressures) are compatible with wall displacements at all points. In addition, solutions may be obtained by this method for stages intermediate to the final configuration as well as allowing for multiple anchors. However, it must be emphasized that the procedure is a "gravity turn-on" and does not take into account the cumulative effects of the construction sequence. The greatest uncertainty in the method is in selecting the soil stiffness parameters, consequently the method should be used to evaluate the sensitivity of the solution to variations in soil stiffness. Terzaghi (1955) has indicated that the forces in the system are relatively insensitive to large variations in soil stiffness, although calculated displacements are significantly affected. Although the forces and displacements are compatible in the solution, it must be recognized that the calculated deflections are only representative of the deformation of the wall and do not include displacements of the entire wall/soil mass.